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Original scientific paper

Spectral Functions of Damage Index (*DI*) for Masonry Buildings with Flexible Floors

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Abstract: Most of the buildings in old city cores of Croatia, built between 1860 and 1920 with wooden floors, are mainly designed to bear vertical loads. In this paper we propose a methodology for seismic vulnerability assessment of unreinforced masonry buildings with flexible floors. The methodology is based on the calculation of Damage Index (*DI*), a numerical value indicating the level of structural damage. In this methodology, the structure is represented using an SDOF model determined by damping, weight, elastic base shear capacity, elastic stiffness and post-elastic stiffness. Using accelerograms of earthquakes, step by step time-history numerical integrations are provided along with the results: top displacement, yield excursions, cumulative energy and base shear–displacement. These results serve as parameters which are then input in the formula for Damage Index (*DI*). The results of the paper are presented in the form of diagrams with *DI* values on the y axis and fundamental period of the structure on the x axis. These spectral functions of *DI*, along with knowledge of fundamental period and chosen accelerogram, can be used to quickly determine the level of damage for unreinforced masonry buildings with flexible floors.

Keywords: Damage Index (*DI*); flexible floors; seismic vulnerability; unreinforced masonry (URM)

1 INTRODUCTION

Communities around the world face natural hazards, therefore it is important to have an approach to natural hazards developing not only disaster response systems but considering disaster risk preparedness and mitigation as an integral part of sustainable development. Amongst the strongest and most destructive forces in nature are earthquakes. Due to increased population concentration and urbanization in earthquake prone areas, government and academia have started showing interest in determining the seismic risk of building stock [1, 2].

Damage of a structure and its elements can be defined as a certain degradation of the building due to its structural features caused by the action of seismic load of a specific intensity. Damage index (*DI*) presents the level of structural damage and is previously defined by the formula by authors Morić et al. [3, 4, 5]. The structure is represented using an SDOF model determined by weight, elastic base shear capacity, damping, elastic stiffness and post-elastic stiffness. Using accelerograms of earthquakes, step by step time-history numerical integration can be provided along with the results: top displacements, yield excursions, cumulative energy and base shear–displacements. These results serve as parameters which are then input in the formula for *DI*. This methodology was verified for RC frame and wall structures and the spectral functions of *DI* (plot of a number SDOF models with different fundamental periods) were created for RC framed structures. The aim of this study is to extend the current research of Morić considering seismic vulnerability of masonry buildings and to create spectral functions of *DI* for URM with flexible floors.

A significant number of buildings, which are built from stone and masonry blocks, are not following any provision and they are not in accordance with earthquake-resistant design. For these old buildings it is necessary to evaluate the level of risk [6].

As it is stated in [7], most of the buildings in old city cores of Croatia were built between 1860 and 1920. A number of deficiencies have been detected for such buildings: wooden floors are mainly designed to bear vertical loads; either due to repeated in-plane disturbance or low shear bearing capacity, masonry walls have the tendency to crack; no suitable linkage between masonry walls and wooden floors exist. Other building specific deficiences including soil and foundation problems as well as material degradation have also been evidenced.

Intensive researches in recent years have been conducted in earthquake assessment of cultural heritage in seismic areas. The reason for this high interest is the fact that heavy mass of masonry, complex geometry, anisotropy and high heterogeneity represent the main difficulties for the seismic analysis of these buildings [8]. For a building of cultural heritage, most attention is paid to the modelling of individual buildings and assessment methods based on non-destructive procedures [9, 10, 11].

Therefore, the procedure for assessing the vulnerability of a historical building consisted of flexible floor structures has to be much more detailed and requires more computer resources and special equipment compared to empirical methods. Perhaps the key for more rapid assessment of these buildings lies in a hybrid approach as a combination of empirical and analytical method validated with experimental results to obtain more reliable and quantitative results for the group of buildings.

2 MEASURE OF STRUCTURAL DAMAGE

In order to quantify degradation in structures, damage models are used as the main tools. Damage ratios (*DR*) or damage indices (*DI*) can be used to estimate the damage, where the main goal is to decide whether the building is suitable for use or not, also in checking the seismic analysis of structures, and for the prediction of seismic behaviour of new types of structures.

DI represents a mathematical model describing the state of structural damage and is mainly directly related to the actual damage caused by earthquakes. It can be determined using either the dynamic response of a structure or the response of a structure to a given loading pattern. Economically, *DI* represents the proportion of funds needed for the repair of earthquake damaged structures and the resources needed for the construction of a similar structure. *DIs* have proven to be suitable tools for numerically quantifying the damage of structures obtained under earthquake loading [5].

During last decades, several approaches as well as critical reviews for the assessments of structural damage have been analysed [5, 12, 13]. Damage indices can be categorized as global (considering the whole structure) or local, as deterministic or probabilistic indices [14, 15], structural or economic indices [16, 17], structural or non-structural indices [16]. Other classifications could imply indices based on energy, deformations or stiffness, or a combination of more of them, low-cycle versus high-cycle fatigue indices, cumulative or noncumulative indices, global indices as a weighted average of local indicators or modal indices, etc.

3 PROPOSED METHODOLOGY FOR SEISMIC VULNERABILITY ASSESSMENT OF MASONRY BUILDINGS WITH FLEXIBLE FLOORS

In order to perform a fast seismic vulnerability assessment, the method proposed in this paper requires the use of suitable *DI* spectral functions (plot of a number of SDOF models with different fundamental periods).

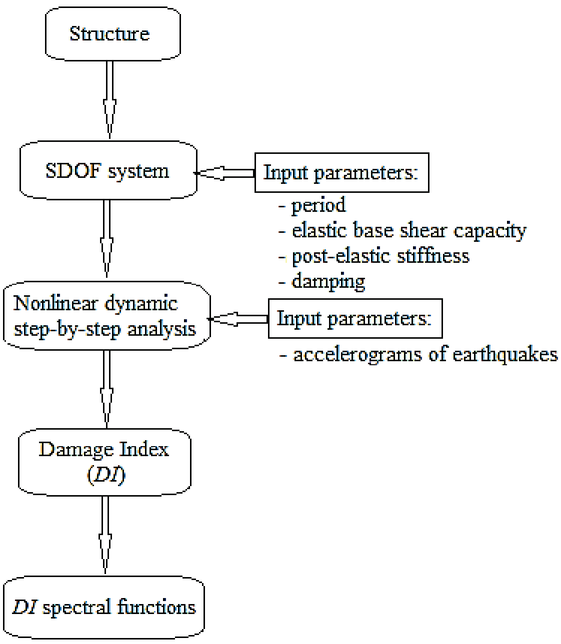


Figure 1 Proposed methodology for seismic vulnerability assessment

The variation of *DI* values for a series of single-degree-of-freedom (SDOF) systems, with structural properties related to unreinforced masonry structures (URM) with flexible floors subjected to multiple earthquakes with different characteristics, forms the damage spectral functions of *DI* [5, 18]. To accomplish that, a series of dynamic time history analyses using software NONLIN (which implements step-by-step dynamic analysis using time histories of earthquake accelerograms) were run. In the following, the main parts considering the methodology for fast seismic vulnerability assessment based on *DI* is provided: the formula for the *DI*, the proposed structural properties of URM buildings and the determination of the earthquake accelerograms (Fig. 1).

3.1 Damage Index (*DI*) Formula

The values of *DI* vary between 0 and 1 (or 100 %), with 0 representing the undamaged state and 1 total failure. *DI* may include one or more variables of vulnerability, some of which include ductility, stiffness, energy, deformation of specific sections and/or elements, floor dispacements, etc. [5].

Two basic procedures can be applied when a structural damage index is computed [19]:

a) Demand versus capacity procedure. This procedure is based on estimation of some demand on a member, substructure or structure, and estimation of the corresponding capacity. In this procedure, demand and capacity could involve strength, displacement, deformation and energy dissipation. In each case, the damage parameter may be based on a single maximum value, some cumulative value or a maximum range.

b) Procedure based on degradation. This procedure is based on estimation of a property for a member, substructure or structure in its undamaged state, and a corresponding estimation in its damaged state. In this procedure, possible choices for the structural property could involve strength, stiffness and energy dissipation capacity. Period lengthening represents one measure of stiffness degradation, while more direct computations of change in stiffness represent other measures.

As it can be seen from above, strength, stiffness and energy dissipation could be possible choices for the demand and capacity or for structural property for both procedures. Since the stiffness degradation of the structural elements often cannot be included in software for seismic analysis, the second procedure can be applied only if strength degradation and stiffness can be modelled appropriately in the analysis [19].

It has been established in previous works [3, 4, 5], that a regular structure can be modelled using an SDOF model with defined weight, damping, elastic base shear capacity and elastic and post-elastic stiffness. For that model, seismic response analysis can be performed as a simplified non-linear dynamic analysis with the time history function of ground motion as input load. *DI* can be defined as a linear combination of plastic deformations, stiffness degradation and energy dissipation of a building during an earthquake:

$$DI = \frac{1}{30}\left[D + \Delta K + \sqrt[3]{\left(\frac{N_Y E_H}{W} \right)} \right] \tag{1}$$

where: $D = u_{\max}/u_y$ is required ductility defined displacements; is relative degradation of stiffness at the end of the earthquake; $\Delta K = K_{el}/K'$ is initial stiffness; $K' = BS_{\max}/u_{\max}$ is residual secant stiffness at the end of the earthquake; N_Y are the number of yield cycles achieved during the earthquake; E_H/W is the hysteresis energy dissipated during an earthquake.

DI can describe the condition of the structure after an earthquake by relating its values with level of damage states, in this case according to EMS-98 [20], which is presented in Tab. 1 [4].

Table 1 Correlation between *DI* values and EMS-98 damage grades

DI	Description of structural damage	Damage grade (EMS-98)
$0 < DI \leq 0.3$	insignificant	1°
$0.3 < DI \leq 0.5$	moderate	2°
$0.5 < DI \leq 0.8$	severe	3°
$0.8 < DI \leq 1.0$	heavy	4°
$1.0 < DI$	extremely high level or collapse	5°

3.2 Damage Index (*DI*) Formula for Masonry Buildings with Flexible Floor

A detailed analysis of the dynamic properties and post elastic parameters of structural elements of RC frame and wall structures was conducted in the work using available databases of performed experiments. This investigation served for the sensitivity analysis, which indicated that the greatest influence on the damage level (e.g. *DI*) of a structure have fundamental period of the structure and the yield base shear [4].

The aim of this paper is to extend the research results obtained for RC buildings with the results reported by Morić [12, 18, 21, 22] for masonry buildings. In Morić [22], the important seismic resistance parameters were suitably varied during the design process. The procedure was based on the relationship between the structural capacity (DI_s – supply) and the structural response (DI_d – demand). When $DI_s<DI_d$ the structure, storey, element or section is seismic resistant for the considered earthquake intensity, i.e., it can withstand the earthquake without collapsing. A systemization of the obtained results was performed in order to determine the relationship between the seismic resistance of buildings with different floor structures and those with "absolutely rigid floor structures".

DI_{flex} is presented as a mean value of partial coefficients of seismic condition which are the function of change of structure response parameters as follows [22]:

$$DI = \frac{W_d}{2.4 \cdot BS_y \cdot U_y} + \frac{D_d}{3} + \frac{(T_i / T_0)_d}{1.5} \tag{2}$$

where $\frac{W_d}{2.4 \cdot BS_y \cdot U_y}$ is dissipated energy (BS_y is the yield base shear and U_y is the yield displacement), $\frac{D_d}{3}$ is the maximum displacements and $\frac{(T_i/T_0)_d}{1.5}$ is the change of fundamental period.

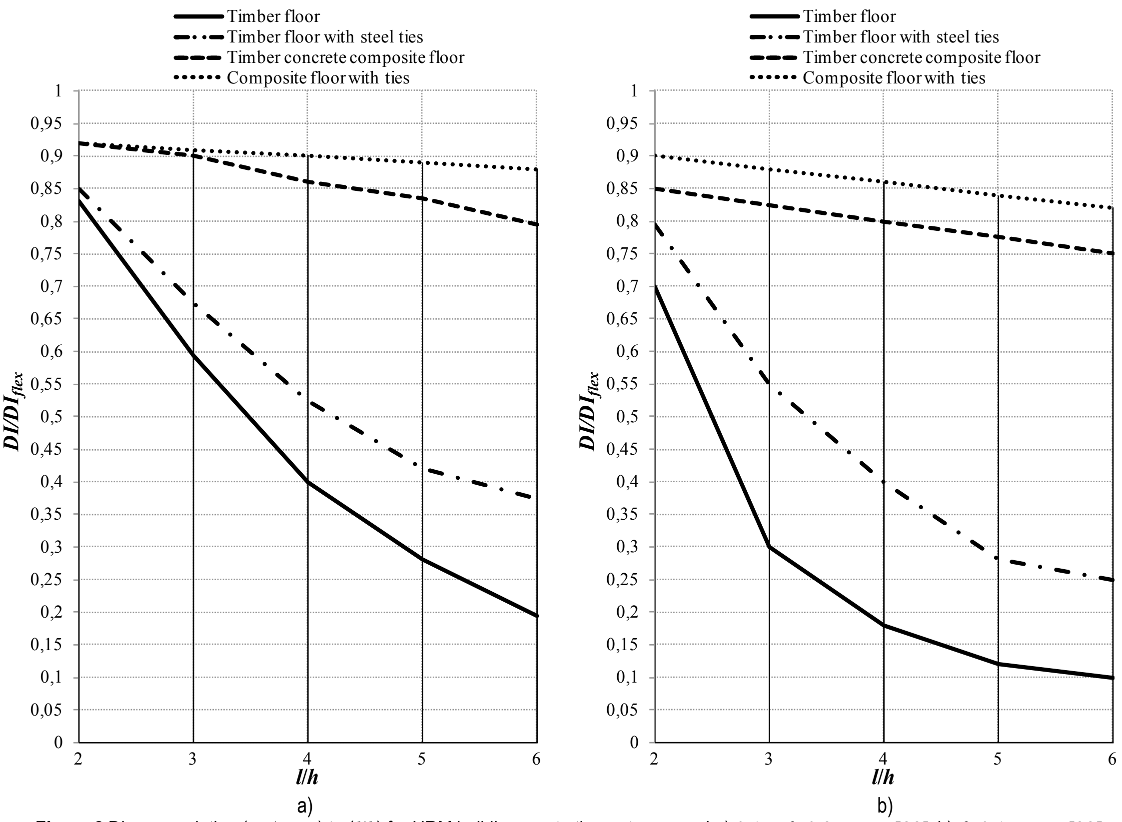


Figure 2 Diagram relating (DI/DI_{flex}) to (l/h) for URM buildings up to three storeys and a) $0.15<f_t<0.25$ MPa [22] b) $f_t<0.15$ MPa [22]

For each of the analyzed building types in the work [22], the values of reduction coefficient (DI_i/DI_{RC}) are calculated for three values of the geometrical ratios (l/h), where l is the wall length perpendicular to the direction of earthquake and h is a storey height. Apparently, slenderness is the most important factor influencing the behavior of a wall, and is often provided using the ratio h/l [8]. For the particular type of building, diagrams describing the reducing of the seismic resistance (DI_i/DI_{RC}) as a function of the geometrical disposition (L/h) are made. Diagrams are actually regression curves in the range $2<(l/h)<6$, which is shown in Fig. 2a for N=3 and 0.15 MPa$<f_t<$ 0.25 MPa (N is the number of storeys) and in Fig. 2b for N=3 and $f_t<$ 0.15 MPa.

The validation of the research was carried out by comparing the results of the experiments performed in the Building and Civil Engineering Institute, Ljubljana, Slovenia between the years 1990 and 1992 [23].

When masonry buildings are in question, using these studies as well as a series of tests conducted on the capacity of masonry buildings, the following algorithm was applied [24]:

1. For reinforced masonry buildings confined with vertical tie-columns it is recommended to apply the same *DI* as for the reinforced concrete shear wall buildings with a reduction factor.
2. For confined masonry building *DI* determined with the following parameters shall be adopted: T=0.05N, BS_y = 0.1W and K_2 = 0.
3. For URM buildings it is recommended that *DI* is the same as for confined masonry divided by the coefficient (DI/DI_{flex}) ≤ 1 according to the curves provided in the work [22] as functions of the ratio l/h and the type of ceiling.

4 NUMERICAL ANALYSIS OF SDOF MODEL OF MASONRY BUILDINGS WITH FLEXIBLE FLOORS

In dynamic analysis, input as seismic load should represent accelerogram with expected ground motion events on the observed location. With the help of software REXEL, on the basis of already happened earthquakes, knowledge of ground properties (type B) and the seismicity of the area of Osijek, 7 earthquake records matching the parameters were selected [25]. The selected records of the earthquakes (Tab. 2) were originally expressed in cm/s^2, and then are scaled to be obtained in units of gravitational acceleration g. We selected seven real ground motion records compatible with EC8 [34] for a peak acceleration of 0.1g, soil category B, and spectrum Type1. This set of ground motion records was taken from the European Strong-Motion Database (ISESD). The ISESD databasecontains earthquakes from the Europe and Mediterranean, from where a set of 7 records of the ground motions, which had the lowest possible average deviation from the target spectrum (Fig. 3) was chosen using the software REXEL 3.5 [25]. The next requirement that had to be fulfilled is that, in the range of the periods (T) from 0.15·T and 2·T, the margin of tolerance is 90–130 % of the target spectrum (Fig. 3). Tab. 2 shows data on the selected set of seismic ground motions records, which were recorded on soil type B, classified according to EC8 [26].

We then scaled the accelerograms to 0.05g, 0.1g, 0.15g, 0.2g, 0.25g, 0.3g, 0.35g. *DI* was calculated using Eq. (1) for parameters of structural response of nonlinear time history calculation for every SDOF concept and chosen accelerogram.

Taking into account all the combinations of the structure parameters defined above, 13 various structures were obtained. Each of these structures was subjected to nonlinear seismic time history analysis using 7 different earthquakes with peak accelerations ranging from 0.05g to 0.35g.

This made a database that can be the basis for enabling the analysis of potential seismic vulnerability values of building for a specific area that can provide insight into the real state of the construction and analysis of the level of damage before or after an earthquake.

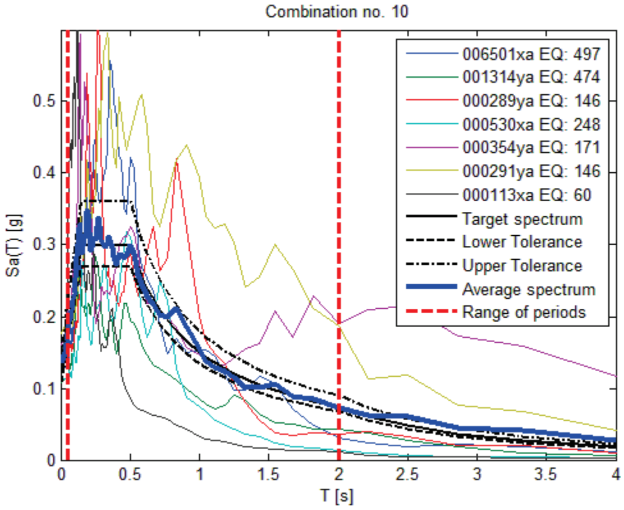


Figure 3 Response spectrums for 7 ground motion records with 5 % damping. It was based on the target spectrum EC8 (spectrum type 1, soil type B) with a peak ground acceleration of 0.1g

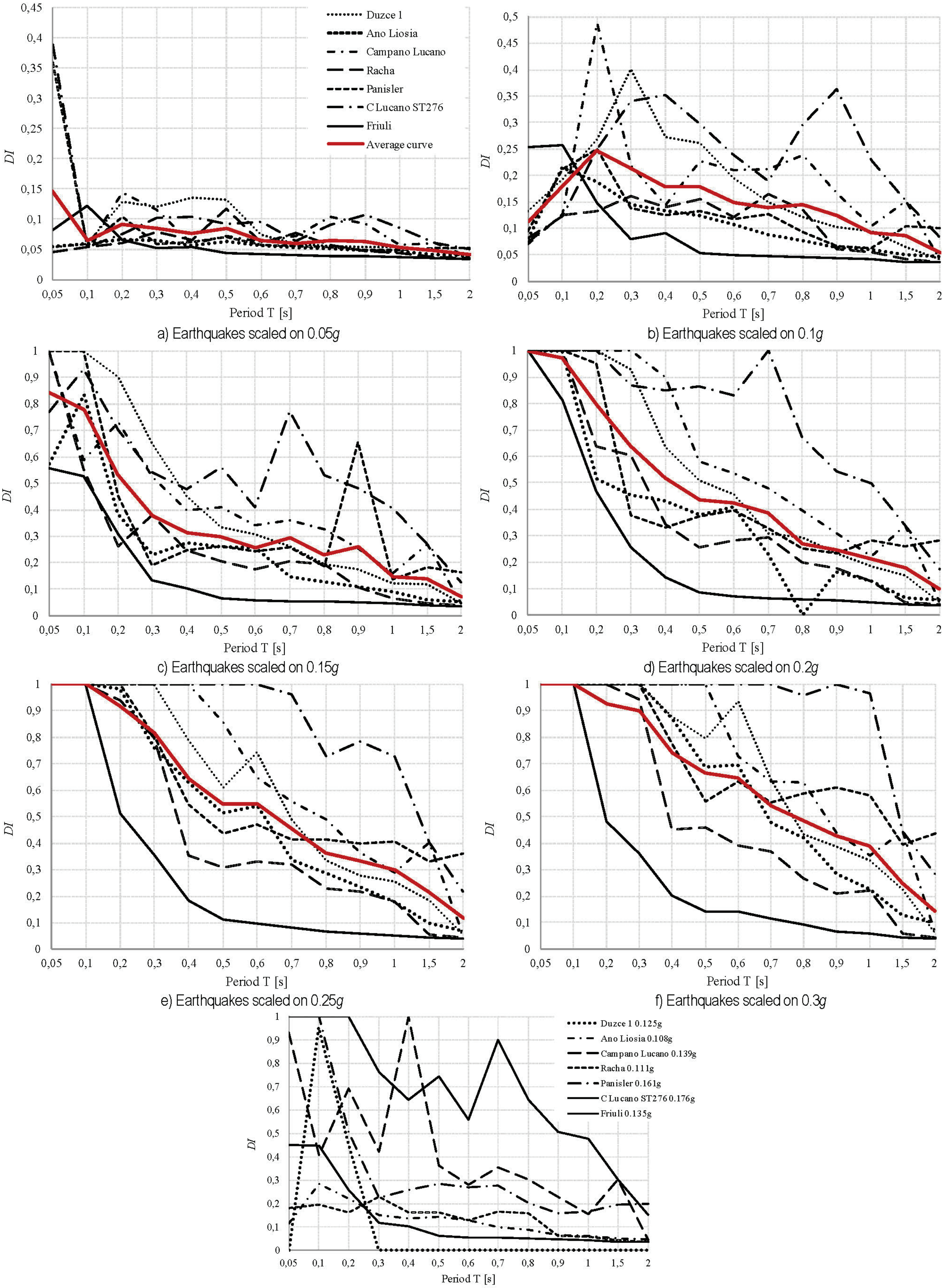
By knowing the specific parameters of the structure (layout, height, structural type, material), it is possible to apply the spectral function in order to obtain the *DI* values which determine the state of the structure in terms of predicting damage from seismic load of a specific intensity.

A series of non-linear dynamical analyses was performed with the time history function of ground motion for earthquake input load and for each of the important parameters of structures that interpret dynamical and post-elastic properties of the structure. Since the SDOF models are defined by damping (ξ), weight (W), yield base shear capacity (BS_y), elastic stiffness (K_e) and post-elastic stiffness (K_2), various structures are obtained by varying these parameters.

Given that the selected buildings are made of masonry bricks, these parameters are selected in accordance with their design characteristics. Since masonry construction does not have post-elastic stiffness i.e. they are calculated with little absorption capacity, the amount K_y is 0. Base shear force at ground floor BS_y is expressed as BS_y = 0.1W since it represents the structure with low elastic earthquake resistance. Damping during calculation was constant and amounted to 5 % because it has been shown as the least important parameter for the level of damage to the building under earthquake loading.

All calculations are performed with the aid of software NONLIN developed by Charney [27]. During the calculation all constructions are modelled as SDOF systems with constant weight W = 1000 kN, and are classified according to their basic parameters:

- period ΔT = 0.1 s (T from 0.05 s to 2 s)
- limit of elasticity BS_{el}/W, expressed as BS_{el} = 0.1W
- post-elastic behaviour expressed as K_y / K_{el} where K_y = 0 K_{el}
- damping of 5 %.



a) Earthquakes scaled on 0.05*g*
b) Earthquakes scaled on 0.1*g*
c) Earthquakes scaled on 0.15*g*
d) Earthquakes scaled on 0.2*g*
e) Earthquakes scaled on 0.25*g*
f) Earthquakes scaled on 0.3*g*
g) Original earthquakes

Figure 4 Spectral damage functions for URM with flexible floors defined by the following parameters BS_y=0.1WK_2=0$K_{el}\zeta$=5% and a) earthquakes: scaled on 0.05*g*, b) Earthquakes scaled on 0.1*g*, c) Earthquakes scaled on 0.15*g*, d) Earthquakes scaled on 0.2*g*, e) Earthquakes scaled on0.25*g*, f) Earthquakes scaled on 0.3*g*, g) Original earthquakes

Table 2 Main properties of used earthquakes

	Earthquake						
	Duzce 1	AnoLiosia	Campano Lucano	Racha	Panisler	Campano Lucano	Friuli
Station ID	ST3141	ST1101	ST95	ST200	ST133	ST276	ST35
M_W	7.2	6	6.9	6	6.6	6.9	5.3
Epicentral Distance (km)	26	17	48	40	33	16	21
$PGA_{,}x$ (m/s^2)	1.2273	1.171	1.0578	1.0967	1.2389	1.5256	1.3304
$PGA_{,}y$ (m/s^2)	1.5452	1.0661	1.3625	1.0317	1.5754	1.7247	1.7013

A plot of a number of SDOF models (specified by damping, elastic base shear capacity and post-elastic stiffness) with different fundamental periods will create damage of spectral functions. Thus, by knowing the parameters of an SDOF system (weight, post-elastic stiffness, damping and base shear), a response of an URM building with flexible floors to a given earthquake can be determined just by looking at the graph. Using the spectral damage functions of *DI* in Figs. 4a) to 4g), one can determine the possible value of *DI* for a given period of the defined structure. The curve of mean values *DI* (average curve) is marked in black.

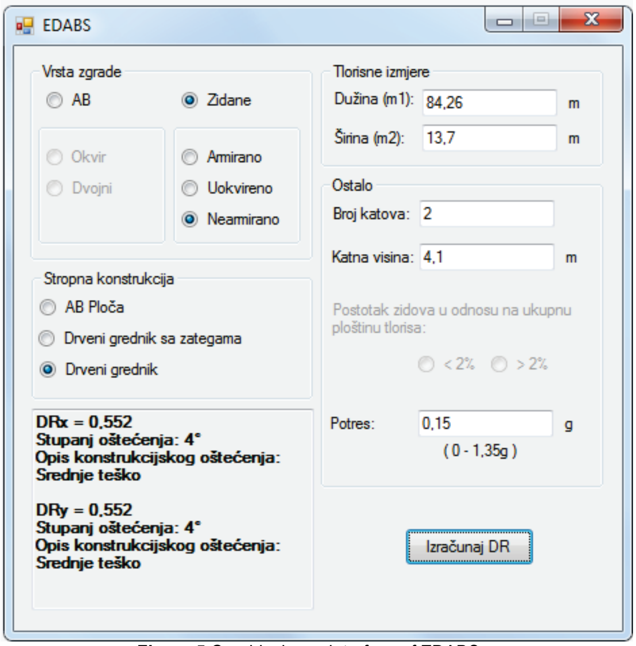


Figure 5 Graphical user interface of EDABS

5 IMPROVEMENT OF EDABS SOFTWARE FOR MASONRY BUILDINGS WITH FLEXIBLE FLOORS

Using a database of *DI* spectral functions as well as the results and expressions obtained from experiments, a program (EDABS) that relates structural dimensions and seismic loads with the dynamic properties of structures and the *DI* was created and presented [28]. Graphical user interface is presented in Fig. 5. This program allows for fast earthquake damage analysis of buildings. This software determines the *DI* using only the structural dimensions of buildings, structure type of RC structures and the peak earthquake ground acceleration as input. The software EDABS is expanded with the researches of Morić [18, 21, 22] considering seismic vulnerability of masonry buildings using proposed methodology for seismic vulnerability assessment in Fig. 1. The software has been expanded with the database in this paper regarding the set of ground motion records compatible with EC8 [26] for a peak acceleration of 0.1g, soil category B, and spectrum Type1.

6 CONCLUSION

In recent decades, estimation of the potential damage from earthquake loading is imposed as a very important issue in the construction industry. *DI* values are a suitable tool for the numerical quantification of the damage in structures sustained under earthquake loading.

Nonlinear dynamic analyses were carried out using an ensemble of time-histories, corresponding to a given level of ground motion, for many buildings with random structural characteristics. The output of each nonlinear analysis was used to calculate a global damage index related to a particular damage state according to EMS-98 in order to describe the level of structural damage after an earthquake.

It can be concluded that the aforementioned method of determining the *DI* for masonry structures can be used to assess the seismic vulnerability of urban regions. With this method, which is relatively quick and easy to access, the level of potential damage to the structure may be provided. Although the results are expected, it is necessary to further expand this study in order to obtain the results of potential damage to other masonry constructions under the seismic load.

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